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REMOTE SENSING FOR OCEANOGRAPHY: PAST, PRESENT, FUTURE

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ABSTRACT

Oceanic dynamics has traditionally been investigated by sampling from instruments in situ, yielding quantitative measurements that are intermittent in both space and time; the ocean is undersampled. The need to obtain proper sampling of the averaged quantities treated in our analytical and numerical models is at present the most significant limitation on advances in physical oceanography. Within the past decade, many electromagnetic techniques for the study of the earth and planets have been applied to the study of the ocean. Now satellites promise nearly total coverage of the world's oceans using only a few days to a few weeks of observations. This paper presents both a review of the early and present techniques applied to satellite oceanography and a description of some future systems to be launched into orbit during the remainder of this century. Both scientific and technologic capabilities are discussed.

INTRODUCTION

Oceanic processes have traditionally been investigated by sampling from instruments in situ, yielding quantitative measurements that are intermittent in both space and time. The past two decades have seen the development of new observing systems such as the STD, current meters, and SOFAR floats. These devices give continuous records in one dimension, either instantaneously in the vertical, or at a fixed point, or approximately moving with a water parcel. Arrays of these instruments have greatly increased our awareness of the space-time variability in the oceans, be it due to internal waves, mesoscale eddies, or fluctuations in the general circulation itself. The need to obtain proper sampling of the averaged quantities treated in our analytical and numerical models is at present probably the most significant limitation on advances in physical oceanography.

In principle, space-based techniques can offer substantial information important to this four-dimensional jigsaw puzzle. Global coverage of broad scale surface features such as wind stress, sea level, surface waves and currents, and temperature at time intervals which are short enough to be effectively continuous gives an enormous potential advantage over shipborne techniques. High resolution images of temperature or color or microwave emissivity allow unique visualization of near-surface processes such as internal waves and eddy formation. Such visualizations can greatly extend the interpretation of conventional measurements, and allow considerable economics and a new kind of strategic planning of ship operations, which

are rapidly becoming intolerably expensive. Communications with sensors on fixed and drifting buoys, and the location of non-fixed systems through satellites make possible all sorts of composite subsurface measurement systems which would otherwise be quite impracticable.

Remote sensors operating from the vantage point of space will never replace direct measurements and acoustic remote sensing, because the ocean is essentially opaque to electromagnetic radiation, but satellite remote sensing observing and data relay and platform location techniques should play a substantial role that needs to be systematically recognized and exploited in future programs of ocean sciences research.

Such exploitation requires a developing synergism between specific space-based techniques and missions, on the one hand, with research experiments on important oceanographic problems that benefit from those techniques, on the other. The uncertainties associated with inference from remote sensing, and the difficulties of reconstructing the overall picture from observations in situ imply that the acceptance of new information will come only after a painstaking program of observing system intercomparisons and confidence building case studies. These will require long-range commitment by leading oceanographic scientists and satellite instrument specialists.

Recent experience with sensors on Skylab, GEOS-3, Nimbus-7, and Seasat designed for ocean observation underline the need to include from the beginning explicit planning for validation/control observations, and a substantial data collection, archiving, and distribution effort. To do otherwise would risk not extracting the full advantage of the very large investment in the satellite portion of the system.

New observing tools can transform the basic perception of old problems, but only after their interpretation has been established, necessary corrections have been applied, and calibrations and error estimates are known. There are few applicable standards for "surface truth". Indeed, the space-derived information has fundamentally new characteristics, such as horizontal averaging over larger regions and the feasibility of averaging over longer times (through repeat observations), so that it is attractive as a unique complement to information derived from direct observations. The orderly evolution of composite systems also needs long-range vision and stability of institutional arrangements which transcend the traditional boundaries of funding agencies. The process of assimilation and adjustment to these new opportunities will be a long and sometimes painful one.

The following descriptions of possible research activities are not ordered according to priority, but illustrate a range of important and challenging scientific applications. Many such research objectives could be met by a few satellite flight programs, and there are many ways in which observing systems may be combined on any particular flight. No attempt is made here to discuss such matters.

WIND STRESS

The wind stress at the surface is one of the major driving forces of oceanic circulation. There are no systematic observations with which to test the performance of various models of ocean circulation and ocean response to the atmosphere. Ship observations of wind provide some coverage in regions served by commercial shipping; ship observations, however, are noisy (i.e., may contain undetectable errors) and uncalibrated (e.g., for ship effects) and must be processed carefully before use.

Remote sensing systems mounted on polar orbiting satellites can rapidly and frequently sample nearly the entire earth's surface. Although numerous satellite-borne active and passive systems (altimeters, radiometers, and scatterometers) have been used to measure wind speed, microwave scatterometers have demonstrated a decided advantage due to their ability to measure the vector winds (speed and direction) needed as inputs for oceanographic and meteorological studies.

The use of active microwave systems for the measurement of oceanic winds resulted from the World War II development of radar systems for air defense. Research into the causes of "sea clutter" was conducted in the U.S. and U.K. following the end of that war. Experimental studies in the 1950's and 1960's established an apparent correlation between backscatter at moderate incidence angles and surface wind speed. Extensive series of airborne radar measurements by the Naval Research Laboratory utilizing a four-frequency pencil-beam scatterometer, and NASA/JSC utilizing an airborne fan-beam scatterometer at Ku-band frequencies established an approximate power-law dependence of normalized radar cross section (NRCS) on wind speed. In the early 1970's, NASA developed an improved pencil-beam aircraft scatterometer (AAFE RADSCAT) that was stable and demonstrated good absolute calibration. Field experiments improved and refined the approximate power-law relationship between the NRCS and the wind speed at incidence angles from 20° to 70°. In addition, by obtaining data from circle flights, the relationship between the NRCS and azimuth angle relative to the wind was examined. The amplitude of the NRCS varied with both wind speed and azimuth angle, and the nearly harmonic variation with azimuth angle made it possible to determine wind direction by radar measurements of the same spot of the ocean at two azimuth angles.

A pencil-beam radiometer/scatterometer was flown aboard the Skylab missions SL-2, SL-3, and SL-4 in 1973-77. Since the scatterometer was a single beam, only a single measurement of the NRCS at one value of azimuth angle was obtained from each portion of the sea surface. Nonetheless, these experiments demonstrated that wind speed scatterometry was feasible.

The Seasat-A Scatterometer System (SASS), a four antenna fan-beam dual polarized Ku band system was flown aboard Seasat from June to October 1978. NRCS measurements from the fore and aft beams were combined to give estimates of wind speed with up to four possible directions (unfortunately called "aliases"). This was a major accomplishment. Using SASS data, the first global nearly synoptic maps of

wind speed and direction have been constructed by P. Woiceshyn and others at JPL.

In 1988, the U.S. Navy plans to fly NROSS, an oceanographic satellite which will carry NSCATT, a NASA scatterometer. An additional antenna on each side of the spacecraft (making six in all) will reduce the "alias problem" to an ambiguity of 180° for about 95% of the measurements. The NRCS will be measured with a spatial resolution of 25 km. In the opinion of scientists who are trying to develop better models of the ocean circulation, one of the greatest needs, at present, is a coherent, calibrated long-term data set of surface stress or wind over at least the tropical zone, and preferably over the globe. The Seasat data processing effort and the experience with the validation program indicate what explicit measurements must be made in situ to facilitate the use of the basic observations. The Seasat data offer an enticing glimpse of future routine wind stress/wind velocity observations globally. But can satellite techniques really supply the information with enough ancillary data for its interpretation? Many special studies will be needed to improve the interpretation of scatterometer observations (i.e., to translate the radar backscatter cross section of capillary waves into stress/speed) and also to identify situations in which there might be other physical or biological factors contributing to the backscattered signal, i.e., to identify reliably the various surface effects that influence the backscatter, and to make adequate corrections.

For example, the return signal from a scatterometer depends on the presence of surface structures with scales in the centimeter range; the usefulness of the scatterometer in measuring wind speed depends upon variations in the intensity and density of these structures as a function of wind speed. One kind of structure involves groups or trains of capillary-gravity waves at these scales, generated directly by the wind stress and perhaps to some extent by weak resonant wave-wave interactions from larger components. At low wind speeds, the local amplitude of these waves trains may not vary strongly with wind speed -- they may reach a local saturation quite quickly -- but the fraction of total area covered by them will surely increase with the wind stress. Also at these scales will be found harmonics of longer, short gravity waves which can be relatively sharp-crested and rich in harmonics. Finally, at these scales also will be found Fourier components associated with the deformed profiles of short, breaking waves as well as the parasitic capillary waves on short gravity waves with relatively sharp crests.

Not much is known in detail about the distribution of these structures and the way that this varies with wind stress. Although our knowledge is sketchy, certain simple properties are reasonably well established. First, the density of microscale breaking waves (wavelengths on the order of 10 cm) increases with wind stress but the amplitude at breaking decreases with wind stress. These profiles are substantially deformed during microscale breaking and contain harmonics at the scales responsible for backscattering. The time scales for generation and decay of wave trains at this scale are short, seconds or tens of seconds at most. Short gravity waves, on the other hand, have growth and decay times longer than this so that (as is usual in the ocean) if they are accompanied by a dominant

longer gravity wave these short waves will be substantially modulated in amplitude and also in wave number by the dominant wave. Short gravity waves are pushed close to saturation near dominant wave crests and this results in a substantially increased density of microscale breaking, parasitic capillary waves, and harmonics of the short gravity waves themselves. On the other hand, in the troughs of the dominant wave, the desaturation of the short gravity waves reduces these. These modulations provide the basis of operation for the scatterometer radar. It is this melange of structures that provides the back-scattered return. The return is clearly a function of wind stress (more properly, u_* / c , where u_* is the friction velocity and c is a representative phase speed of the structures) but observational results still give a great deal of scatter. Enough is known about these structures to be confident that they are also influenced strongly by the slope of the dominant wave present, ak , or Huang's "significant slope" parameter. This dependence is not taken into account in analysis of scatterometer results in which its influence is ignored.

It is evident that there is a considerable need for further research in this area to establish better the characteristics of these small-scale structures, their distribution on the ocean surface, their appearance in response to short-wave/long wave interactions, and so forth. Experiments and observations are difficult. Conventional probe measurements give very restricted information and are extremely difficult to interpret because of the Doppler shifting produced by the orbital velocities of longer waves. Instantaneous spatial definition of the water surface, even in a restricted region, is a tricky problem.

MESOSCALE VARIABILITY

The most energetic mesoscale oceanic eddies are found in the vicinity of strong currents and probably have their source in instabilities. Over most of the ocean, the level of eddy energy is lower; recent studies have concluded that these eddies could be attributed to direct forcing by the variable winds. Their conclusions require some assumptions about the nature of wind spectra. Scatterometer data will go a long way toward replacing these assumptions with solid data, but some field work will also be necessary to extend spectra to finer time and space scales than a scatterometer will provide.

It has also recently been suggested that a significant part of the eddy field of the open ocean away from strong boundary currents is directly forced by fluctuations in the curl of the atmospheric wind-stress. This conclusion was based admittedly on a few observations which show a significant coherent between a seasonal modulation of atmospheric and oceanic fields and on a theoretical evaluation of the oceanic response to forcing by a fluctuating wind-stress field. The theoretical estimate used a model wind-stress spectrum which extrapolated the observed spectral slope at scales on the order of 1,000 km down to scales on the order of 100 km.

To substantiate these suggestions it is extremely important to determine accurately the space-time structure of the wind-stress over the ocean on eddy scales. This would require a spatial resolu-

tion of approximately 50 km and a time resolution of approximately three days.

OBSERVATIONS OF SEA LEVEL (RADAR ALTIMETRY)

One satellite-based effort that has been under discussion for some time has been a topographical experiment (TOPEX). The radar altimeters on the GEOS-3 and Seasat satellites have proven that observations of the distance between the sea surface and a satellite can be obtained to a useful precision, and that a wide variety of important oceanographic and geophysical information can be derived from such observations. Accurate knowledge of the satellite orbital quantities and of the earth's gravity field is necessary to extract the maximum information from the satellite altimeter observations. These matters, as well as the scientific problems to be addressed by TOPEX, are discussed in detail in the report Satellite Altimetric Measurements of the Oceans, prepared by the TOPEX Working Group, published by the Jet Propulsion Laboratory (March, 1981).

The Seasat altimeter showed a precision of about 10 cm in the measurement of the distance between the instantaneous sea surface and the satellite. It is estimated that this precision has to be increased to something like 2 cm to meet the majority of the scientific goals of TOPEX.

A feature of the altimeter is its ability to provide very important and reliable information on the statistics of ocean waves, in particular the significant wave height, $H_{1/3}$. This ocean surface variable is very important for practical purposes, e.g., for marine operations, and also for the study of the development, propagation, and effects of such ocean events as major storm surges.

The radar altimetry could also provide useful information on the topography of the great continental ice sheets of Greenland and Antarctica, which is difficult to obtain by conventional geodetic leveling.

COLOR SCANNER OBSERVATIONS

The Coastal Zone Color Scanner (CZCS) operating on Nimbus-7 is providing a most intriguing new data set. The CZCS instrument was planned primarily for biological investigation, but there is evidence from the data set now available that the patterns seen in the images also trace dynamic oceanic features of great interest.

The intended purpose is to depict, using several bands in the visible (and bands in the red and infrared for correction purposes), the distribution of biological and other scattering agents (chlorophyll, and organic and inorganic suspended materials). It has been realized that, in addition, important information is made available on oceanic structures, sea-surface temperatures, and gross aerosol distribution.

Global and selected regional assessment of living marine resources is the ultimate objective of satellite ocean color sensors. It is abundantly clear from years of shipboard experience that ocean

areas with the most biota of interest are also areas that are dynamically the most complex and variable. As a consequence, the accurate assessment of living marine resources can benefit significantly from synoptic data that are impractical, or virtually impossible, to obtain from ships alone.

Chlorophyll in the ocean, as an index of phytoplankton biomass, is a fundamental quantity that can be estimated using aircraft and satellite remote sensors. To date, no ecologically significant biological quantity other than chlorophyll has been shown to be quantitatively estimatable by satellite.

Synoptic estimates of chlorophyll are important because phytoplankton variability in space and time is a ubiquitous and important feature of the marine environment. [Phytoplankton variability includes not only the density of organisms but also the number of species present (species abundance) and the distribution of individuals among these species (species equitability), but observations of these factors are hardly accessible to shipboard sensing and are inaccessible to remote sensing.] This variability influences both practical problems associated with sampling and estimating abundance within the environment and theoretical considerations related to the structure and dynamics of phytoplankton ecology. Also, the variability of phytoplankton communities is thought to hold a key to understanding the relative importance of physical and biological factors in structuring the marine food web. In addition, there is evidence that the successful modeling of phytoplankton dynamics, and the predictive linkage of phytoplankton production to higher trophic levels, has so far been limited by a lack of synoptic data and limited sampling strategies.

A fundamental problem in marine ecology is to establish both the spatial and the temporal scales in which fundamental physical and biological processes occur and to sample the environment accordingly. Ships, aircraft, and satellites provide alternative, and complementary, strategies for sampling the environment. For example, if chlorophyll concentration, as an index of phytoplankton biomass, is the variable under investigation then ship, aircraft, and satellite "platforms" offer the opportunity to obtain diverse, and often mutually exclusive, experimental information. Shipboard data provide continuity with conventional oceanographic research techniques, can be relatively accurate, can include both vertical and horizontal measurements, but are comparatively limited in both space and time. Chlorophyll data from aircraft systems provide rapid spatial coverage of regional areas, can include both vertical and long-track measurements, can be relatively precise (however, accuracies are the subject of ongoing research), but are limited by the logistics of aircraft, and provide linear (as distinct from areal) coverage. Satellite chlorophyll imagery can provide worldwide coverage of cloud-free areas, can provide repeated routine coverage of regional areas (including those areas that are far from our oceanographic research institutions), but are relatively less accurate without concurrent ship or aircraft data, are limited by cloud coverage, and require more complex image and data processing. The key point is that the living marine resources are unlikely to be assessed adequately without the synoptic perspective, the quantitative areal data, and the quasi-

continuous temporal coverage provided by remote sensors.

Some early use of the Nimbus-7 color images has shown very promising application to the studies of the food web and to illuminating the relationships between the planktonic distribution and the development of young fish. For example, off the California coast, such information has been used effectively to study plankton distribution and the distribution of anchovy spawning. More detailed studies of these kinds would clearly be important contributions to biological oceanography.

DATA COLLECTION AND LOCATION SYSTEMS (DCLS)

A DCLS (Argos) was implemented on the NOAA operational satellites for the Global Weather Experiment, 1979, in cooperation with French colleagues who supplied the hardware and undertook the data processing. This joint arrangement is expected to continue through at least the mid-1980's. It must be remembered that the Argos system was designed primarily to track constant-level balloons accurately for the Global Weather Experiment, 1979; its applicability to other moving platforms was a most useful bonus, but the Argos system has some limitations with respect to other platforms that make it desirable to consider what improvements might increase its support to ocean sciences direct and remote sensing programs. For example, the DCLS for ocean sciences must be able to view a larger number of platforms that Argos does, up to many hundreds of platforms simultaneously, or else some regional projects being considered will not be able to use sufficient numbers of observing sites. The data rate should be increased, but not at the price of more power, so that considerable stored data can be relayed over one pass. Finally, it would be most useful for extensive oceanographic observations if the DCLS design could permit a relatively simple and inexpensive electronic package on the platform, to reduce the unit cost and thus encourage use of larger numbers of observing platforms.

Underwater telemetry can usually be accomplished by relatively low-power acoustic transmission, but long ranges impose severe constraints on batteries, weight, and overall system lifetime. Staging to satellites through a surface intermediary at a known location is an attractive alternative to present techniques, but only provided that a reliable and available satellite link is assured for the foreseeable future. The practicability of large-scale deployment and the scientific utility of drifting buoys was demonstrated in the Global Weather Experiment (GWE), 1979. The buoy program for the GWE was invented and implemented for meteorological purposes. The data fields, however, are also useful per se to define some of the oceanic circulation. The success of the program has stimulated new technical efforts to develop drifters of several types into instruments of broader oceanographic use -- better sensors, reliable thermister chains to obtain temperature profiles, subsurface flotation with tracking and data relay via the sound channel.

An exciting research prospect, feasible in the second half of the 1980s, is exploration of ocean circulation on a global basis using drifters both as tracers of horizontal advection and as platforms from which scalar properties are measured. The objective of

this exploration would be development of worldwide maps of statistical indicators of the general circulation, such a mean flow, eddy energy, and reynolds stress, and of lateral mixing as indicated by drifter dispersion. Eventually, it will be necessary to map variability in various frequency bands at various depths on a global basis. Nearly continuous satellite positioning and data telemetry permit intensive measurement of the upper ocean on a global basis at a reasonable level of effort. Present methods of communicating with drifters at depth are more costly than is ultimately desirable. This will probably limit the use of very frequently positioned subsurface drifters to regional studies in the near future. However, for describing the mean general circulation, including lateral eddy dispersion, the use of satellite-positioned drifters may permit global coverage at a reasonable level of effort.

Assuming that buoy development will proceed as planned (a substantial project is now under way that is supported by NASA, NOAA, and ONR, and that involves collaboration by a group of researchers as well as sensor and buoy engineers) and assuming that a suitable DCLS is available, a substantial program would be feasible to produce worldwide maps of statistics of ocean circulation for four frequency bands: band (i), one cycle per two to 40 days, which is a spectral band containing the results of direct atmospheric forcing; band (ii), one cycle per 40-150 days, the temporal mesoscale; band (iii), one cycle per 150 days to the length of a feasible program, say three to five years, which contains the secular climatic variability scale; and band (iv), the long term mean, representative of the general circulation. All buoys would include sensors for temperature and pressure, and surface drifters could profile down to 100-200 m. Drifters would be distributed at the surface, in the thermocline, and at an abyssal level, say 3,000-4,000 m. Satellite DCLS or acoustic relay, or a combination, would be used.

SUMMARY

Satellite-borne observing and communication systems offer a variety of techniques to observe and map qualitatively, with high resolution, many oceanic features of importance, and to make measurements that are the basis of quantitative information. These techniques, however, are limited essentially to surface manifestations, and hence there will continue to be a strong need for direct measurements using ships, buoys, moorings, etc., as well as for subsurface remote sensing by acoustic methods.

There are several large scale national and international experiments being planned in the context of the World Climate Research Program (WCRP) for which satellite techniques offer valuable and in some cases unique capability: a large scale study of the heat budget in the North Atlantic; a tropical ocean-atmosphere experiment (TOGA) with emphasis on the Southern Oscillation; and a World Ocean Circulation Experiment (WOCE) for which TOPEX and extensive use of satellite tracked drifters would offer unique contributions.

For any large scale ocean circulation study, it is imperative that we obtain both the global surface wind stress field and the global dynamic topography field: these fields are the necessary

boundary conditions for any ocean general circulation models that may be developed in the near future. TOPEX, NROSS, and the European Space Agency's ERS-1 seem to be the ripest satellite techniques for early implementation.

For the decade of the 1990's, NASA is conducting a study for a comprehensive Earth Observation System (EOS, formerly called System-2). EOS will consist of four parts:

- 1) A set of instruments in low, sun-synchronous Earth orbits dedicated to long term remote sensing of various global phenomena of land, ocean, and atmosphere,
- 2) A global set of land, ocean, and atmosphere in situ instruments to complement the orbiting instruments,
- 3) An international community of scientists who perform the research by analyzing the information gathered by 1) and 2) and controlling their operation, and
- 4) A data communication/computation network that collects the data from 1) and 2) and any required data from other sources (such as operational Earth sensing satellites), operates on these data to increase its information content, stores this information in various data bases and archives, and distributes the information to 3).

The intent of this system is to be interdisciplinary since most geophysical processes involve exchanges occurring at the atmosphere-ocean or atmosphere-solid earth interfaces.

During the past decade, remote sensing of the oceans has been demonstrated to be feasible. It is now time to implement routine satellite observations during the remainder of this century. The processes will be difficult, but the rewards enormous.